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ELEMENTAL ABUNDANCES IN A TYPE I SNR

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ABSTRACT

The Solid State Spectrometer (SSS) on HEAO-2 (Einstein) X-ray observatory observed the X-ray spectrum of Tycho's SNR. The observations show a relative excess of line emission from Si, S, and Ar by $\geq$ 6 compared to that expected from a plasma of solar composition in collisional equilibrium and by a factor of $\geq$ 3 compared to Cas A. Similar excesses are not found for line emission from Mg and Fe. The data suggest that the SN observed by Tycho in 1572 produced significant amounts of Si group elements but did not eject large amounts of Fe as predicted by some models of Type I SN events.

Subject headings: abundances, nebular--spectra, X-ray--supernova remnants

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I. INTRODUCTION

The three youngest galactic SNR (Cas A, Tycho's, and Kepler's) are all less than 400 years old. Observations of these SNR afford the best opportunity to ascertain the composition of SN ejecta. In much older remnants, the original SN ejecta is diluted by the interstellar material swept up by the expanding shock. Historical data suggest that Tycho's and Kepler's SN were Type I events (Baade 1945) while studies of the optical remnant suggest that Cas A is the remnant of a massive progenitor (Chevalier 1977). While there is general agreement that type II SN result from the explosion of massive stars, there is some uncertainty as to whether Type I SN originate from very old, low mass helium stars or from young intermediate mass 2 - 6 M_0 stars (Tinsley 1979). A measurement of the composition of the ejecta of a Type I event could help to distinguish between these two possibilities.

In an earlier paper (Paper I), Becker et al. (1979) presented a detailed spectrum of the X-ray emission from Cas A from which relative elemental abundances of Mg, Al, Si, S, Ar, Ca, and Fe were inferred. In this paper we present a similar analysis of the X-ray spectrum of Tycho's SNR from data taken with the same experiment on the following day. The results from the two remnants are compared and discussed in the context of Type I vs. Type II SNR and equilibrium vs. non-equilibrium models.

II. EXPERIMENT AND ANALYSIS

The SSS experiment has been described in detail by Joyce et al. (1978) and the procedures for analysis of a spectrum accumulated by the SSS have been discussed by Holt et al. (1979) and in Paper I. As in

Paper I, the abundances of He, C, N, O, and Ne are set to their nominal solar values of 0.11, 4.8×10^{-4}, 8.5×10^{-5}, 8.5×10^{-4}, and 1.3×10^{-4} respectively (Meyer 1978). Furthermore, we set the interstellar hydrogen column density to 7.5×10^{-21} cm^{-2}, 3 times the 21-cm N_H as determined by Hughes et al. (1976). The detailed model used in the analysis is an extension of the work of Raymond and Smith (1977, 1979) for X-ray emission from a hot plasma in collisional equilibrium.

Since the angular extent of Tycho's SNR is larger than the SSS field of view ($\sim$ 6 arc min diameter), the Tycho observation was made in five parts. The SSS was pointed at each quadrant of Tycho for $\sim$ 5000^s and at the center of Tycho for $\sim$ 5000 s. The center's of the five fields of view in R.A. (1950) and Dec (1950) are (86$^\circ\!\!.$25,63$^\circ\!\!.$85), (84$^\circ\!\!.$375,63$^\circ\!\!.$85), (84$^\circ\!\!.$375,63$^\circ\!\!.$917), (84$^\circ\!\!.$375,63$^\circ\!\!.$80), and (83$^\circ\!\!.$125,63$^\circ\!\!.$85), respectively. No significant differences were apparent among the five spectra so obtained, so all five observations were combined for the purposes of this analysis.

III. RESULTS

The SSS pulse height spectrum of Tycho's SNR is shown in Figure 1. Strong line emission is readily apparent at 1.85 and 2.45 keV which can be associated with transitions of helium-like Si and S respectively. The data were first fit with a two temperature collisional equilibrium model in which both components were constrained to have the same elemental abundances. The resulting best fit model is superimposed upon the data. We also have drawn a dashed curve which represents the continuum emission from low Z ($Z \leq 10$) elements. The best fit kT for the low temperature component is 0.52 keV. The inferred abundances for Mg, Si, S, Ar, Ca, and Fe are given in Table 1. Inspection of Figure 1 shows the model generally agrees with the data below 3.5, but at higher energies it significantly underestimates the X-ray flux.

The fit to the data can be improved if we relax the constraint that both components share the same elemental abundances. Figure II shows the same data fit by a model in which there is no line emission associated with the 4 keV component. Although at the highest energies the model still falls below the data, the fit at all energies is substantially improved. For this fit, the kT of the low temperature component is 0.46 keV. Again the elemental abundances are given in Table 2.

Equivalent widths for each of the dominant lines are also listed in Table 1. As in the case of Cas A (Paper I), the lines clearly dominate over the X-ray continuum below 3 keV. Therefore the kT inferred for the low temperature component is determined by the ionization structure as reflected in the line emission and not by a thermal X-ray continuum. Fully 50% of the photons we observe are contained in the Si and S lines.

IV. DISCUSSION

Qualitative comparisons between the X-ray spectra of Tycho and Cas A (Paper I) indicate strong similarities. Both spectra are dominated by the helium-like transitions of Si and S but show little emission from hydrogen-like ions (Strong Si line emission was first reported by Hill et al. 1975). Furthermore, as first reported by Davison, Culhane, and Mitchell (1976), at least two thermal components are needed to describe the spectra.

The apparent need to disassociate the line emission from the high temperature component suggests that the hot plasma in Tycho is not in collisional equilibrium. In a recently shock-heated plasma, the electron temperature of the plasma reaches equilibrium more rapidly than the ionization structure of the gas (Itoh 1977; Gorenstein et al. 1974). In effect, even though the electron temperature (and hence the X-ray continuum) may have kT $\approx$ 4 keV, the line emission will be that expected from a much lower kT. This will create the impression of a two temperature spectrum which lacks

both high temperature lines and low temperature continuum. This may be the case for the Tycho spectrum. Based on a broad band, lower resolution X-ray spectrum from HEAO-2, Pravdo et al. (1979) also concluded that the hot plasma in Tycho is far from collisional equilibrium.

In such a situation, the inferred elemental abundances are ambiguous and probably overestimate the true abundances present in the plasma. However, some gross aspects of the elemental abundances in Tycho can still be recovered. In particular, the Si group elements (Si, S, Ar) are clearly overabundant relative to Mg, Fe, and all the low Z ($Z \leq 10$) elements. This is true if the abundances are compared to nominal solar values or those of Cas A from exactly the same modelling procedure as given in Paper I. This is particularly striking in so far as the optical filaments in Cas A are themselves overabundant in Si group elements (Chevalier and Kirshner 1978).

Arnett (1979) has shown that the light curves of Type I SN can be the result of an explosion of a low mass helium star. His analysis predicts that such an event would eject 0.3 M_0 of Fe. In Tycho, 0.3 M_0 of Fe mixed with 3 M_0 of swept-up material would result in a 60-fold overabundance of Fe relative to lower Z elements. No such overabundance is apparent either in the Fe L-lines observed here or in the Fe k-lines (Davison, Culhane, and Mitchel 1976). If anything, Fe is underabundant relative to Si group elements. Therefore, the X-ray data do not support a helium star progenitor model for Tycho's SNR.

It is important to note that both the Cas A and Tycho spectra are consistent with extremely large overabundances of all the silicon-group elements. As pointed out in both Paper I and here, the inferred abundances are dependent on the assumed abundances of lower-Z elements. Therefore,

although these results can speak to the question of the relative amounts of Mg, Si, S, Ar, and Fe, little can be deduced about their absolute abundances. Better estimates will be possible when measurements of the lines from O and Ne (which lie below 1 keV) become available, but detailed non-equilibrium models will still be required for complete consistency.

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TABLE 1: ELEMENTAL ABUNDANCES[a] INFERRED FOR TYCHO

ELEMENT	TWO TEMPERATURE COLLISIONAL EQUILIBRIUM MODEL ABUNDANCES				TWO TEMPERATURE "NON-EQUILIBRIUM" MODEL[d]
	RATIO TO SOLAR[b]	RATIO TO CAS A	EQUIVALENT WIDTH (eV)	PHOTONS[c] CM^{-2}-S^{-1}	RATIO TO SOLAR[b]
Mg	0.10 ± 0.3	0.2	35±100	.0005	0.3
Si	6.0 ± 0.4	3.5	2700±200	.020	12.9
S	13.5 ± 1.2	4.7	2600±250	.0075	32.5
Ar	34.6 ± 1.6	5.0	900±50	.0009	86
Ca	76 ± 35	10	1600±800	.001	195
Fe	0.15 ± .05	0.2	---	---	0.6

[a]Strongly dependent on assumed abundances of He, C, N, O, and Ne. The Fe abundances also depends strongly on assumed hydrogen column density and calculated ice layer thickness. For example, if hydrogen column density increased to 1×10^{22} cm^{-2}, the abundances in the two temperature collisional equilibrium model become .35, 8.1, 15.9, 40.2, and 1.5 respectively.

[b]Based on estimates of solar abundances by Meyer (1978). Error estimates are 1σ based on scatter from 5 independent data sets.

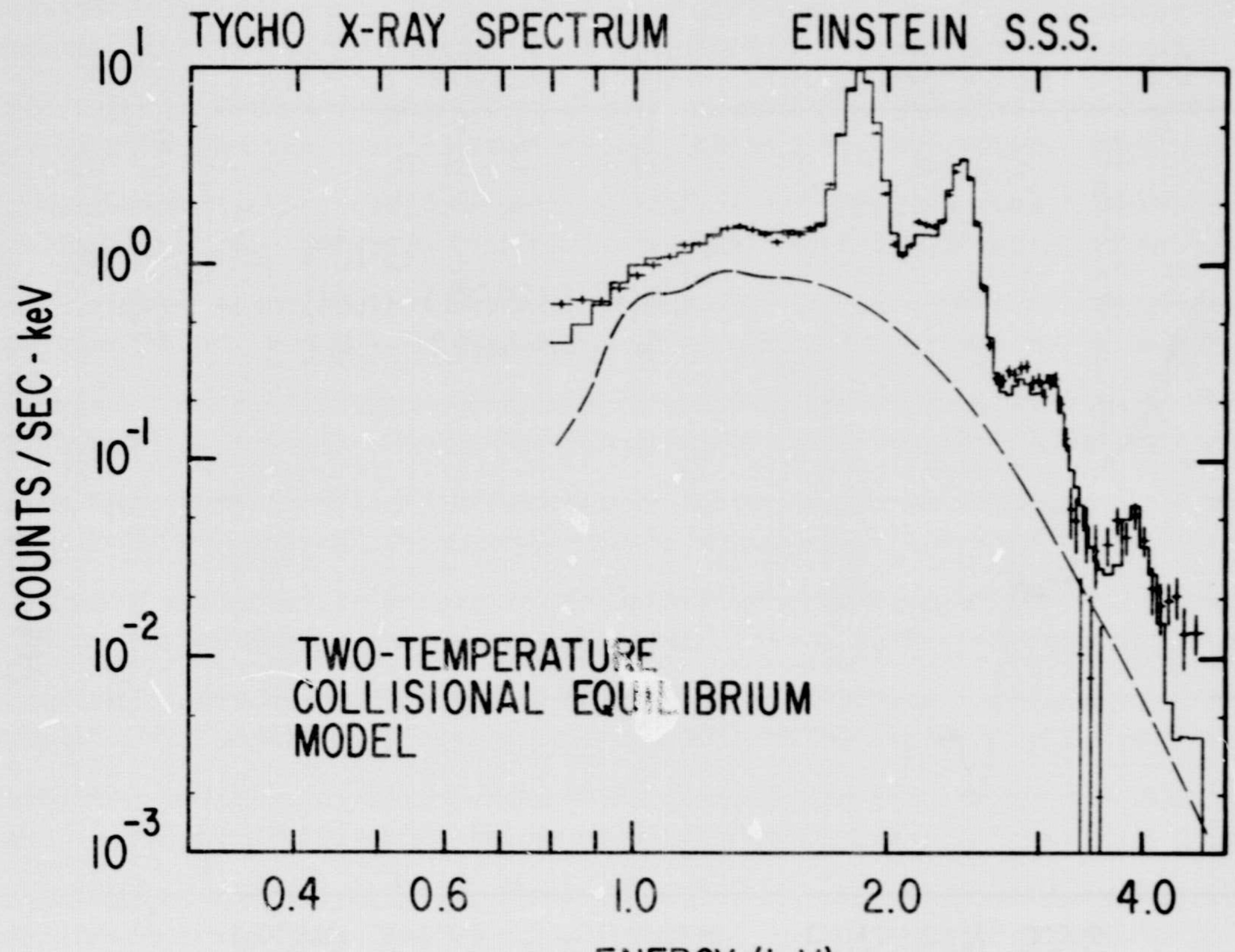
[c]Photon fluxes are lower limits because Tycho larger than SSS field of view.

[d]All lines associated with 4 keV component have been supressed.

FIGURE CAPTIONS

Figure 1 - Pulse height spectrum of Tycho's SNR as observed by the SSS on the Einstein Observatory. Superimposed upon the data is the best fit two-temperature collisional equilibrium model. The lower trace is the estimated underlying X-ray continuum.

Figure 2 - Pulse height spectrum of Tycho's SNR as observed by the SSS or the Einstein Observatory. Superimposed upon the data is the best fit two-temperature "non-equilibrium" model. The model consists of a low temperature collisional equilibrium emission with line contributions from Mg, Si, S, Ar, Ca, and Fe and a high temperature component with no associated lines. The lower trace is the estimated underlying X-ray continuum.



TYCHO X-RAY SPECTRUM
EINSTEIN S.S.S.
COUNTS / SEC - keV
10^1
10^0
10^-1
10^-2
10^-3
TWO-TEMPERATURE
COLLISIONAL EQUILIBRIUM
MODEL
0.4
0.6
1.0
2.0
4.0
ENERGY (keV)